VIII International Conference on Textile Composites and Inflatable Structures
STRUCTURAL MEMBRANES 2017
K.-U.Bletzinger, E. Oñate and B. Kröplin (Eds)

DESIGN OF A COST EFFECTIVE SMALL SPAN TENSILE ROOF

IBRAHIM ALI H.[*], BECCARELLI P. [*], REED V. [†] AND CARPENTER R.[†]

[*] Department of Architecture and Built Environment
The University of Nottingham
University Park, NG72RD Nottingham, UK
Hend.ibrahimali@nottingham.ac.uk
Paolo.beccarelli@nottingham.ac.uk

[†] I2O ltd
Fenstanton, Cambridgeshire, PE28 9HU, UK
vanessa@i2oltd.co.uk
Robert.Carpenter@inside2outside.co.uk

Key words: Tensile Roof, tree-like structures, form-finding, membrane structure, coated fabric, KTP, Innovate UK.

Summary:

Tensile Structures offer a wide variety of membrane forms however, due to the interdependence of form and structural behaviour, only few forms have so far been built. The increasing need for building new tensile forms and investigating innovative solutions for manufacturing and detailing is pushing the lightweight structures market, a strategy adopted by a UK based company, I2O ltd who design and manufacture bespoke innovative tensile structures.

The company held a competition for an innovative, scalable design to complement their product range. The competition was open to all schools, students, sports clubs, restaurants, golf clubs and theme parks and resulted in many entries designed by both school children and adults. The winning design is from Priory Park Infant School in St Neots, UK. The so-called tree-like design is inspired by the school tree emblem and its forest school status. The structure will replace the loss of the school's horse chestnut tree providing shaded creative space for outdoor learning activities. The design challenges for this project derives from two main aspects: I: Transforming the free organic form of trees found in nature into a form that follows a geometric order proven to be structurally stable under different loading conditions whilst maintaining the visual perception of the inspired design. II. Cost-effective solutions for manufacture and detailing of the structure for market development.

The project is designed by Insde2Outside Ltd in the UK, as part of an Innovate UK funded knowledge Transfer partnership with Nottingham University. The project will be manufactured and installed by I2O Ltd who plan to add the structure to its standard products for sale.

1 INTRODUCTION

This project is the result of the ongoing research collaboration between the University of Nottingham and I2O Ltd supported by Innovate UK trough the Knowledge Transfer Partnership – KTP9912 funded to develop novel tensile membrane structures.

The Knowledge Transfer Partnerships is a UK-wide programme conceived to improve the competitiveness of British businesses through the better use of knowledge, technology and skills that reside within the British Universities. The research project aims to meet a core strategic need and to identify innovative solutions to help that business grow with the consequent increase of the overall profitability for the company involved[1].

This paper describes one of the new structures developed during the KTP project. The design is the result of a competition open to all schools, students, sports clubs, restaurants, golf clubs and theme parks. The winner is the project submitted by the Priory Park Infant School (Cambridgeshire, UK) which designed a structure that could replace the loss of the school's Horse Chestnut tree providing a shaded creative space for outdoor learning activities.

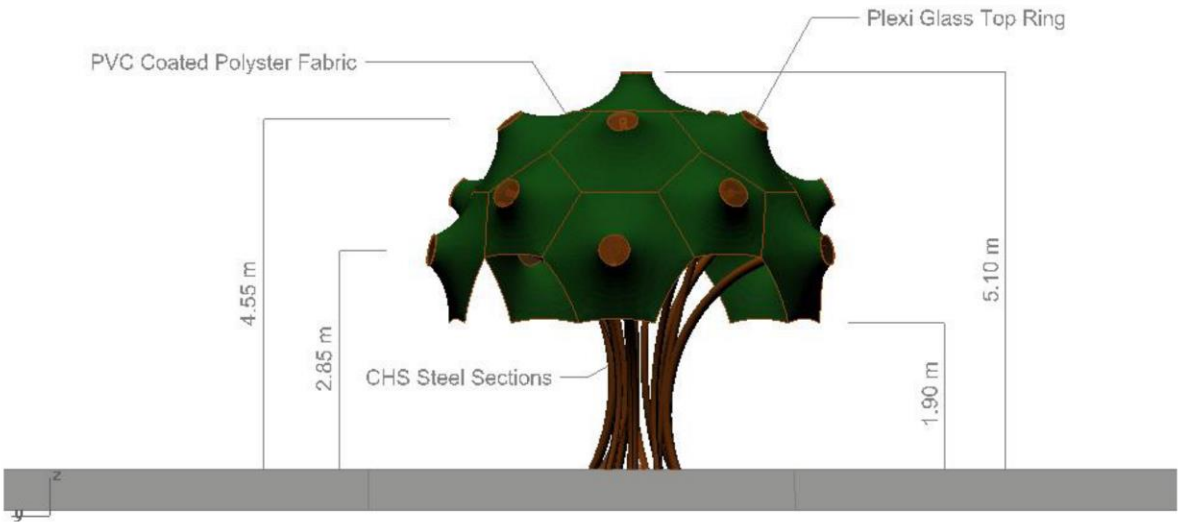

Fig.1. Front elevation of the initial architectural concept.

For the team of researchers from the University of Nottingham, this case study represents an interesting opportunity to test the advanced 3D digital modeling techniques currently available and investigate the correspondence between the digital model and the as-built structure. The comparison includes the match between the final geometry and the surface obtained through the form-finding software, the discrepancy between the results of the finite element structural analysis and the actual structural performance, the inaccuracies due to the flattering of the surface and the subsequent manufacturing of the connections.

I2O Ltd will use the pilot project to investigate the feasibility of bespoke products based on complex geometries and manufacturing techniques characterized by a certain level of unpredictability and challenges which, however, could open new profitable markets for the business.

2 TREE-LIKE STRUCTURES IN ARCHITECTURE

The shape of trees and has always fascinated architects, builders and engineers due to their intrinsic elegance and the interesting structural performance. The impact of this this long-term relationship between nature and architecture has been studied and documented by several researches[2,3] which identified and classified examples of structures inspired by nature form 1400 BC until nowadays. The early examples include columns and capitals used in ancient Egyptian, Greek, Roman, Indian, Chinese and Byzantines palaces and religious buildings. The level of complexity and sophistication reached unprecedented levels during the Gothic period with pointed-arches and vaults designed to mimic the nature using a series of tree-like columns which becomes ribs in correspondence of the vaults (Fig.2).

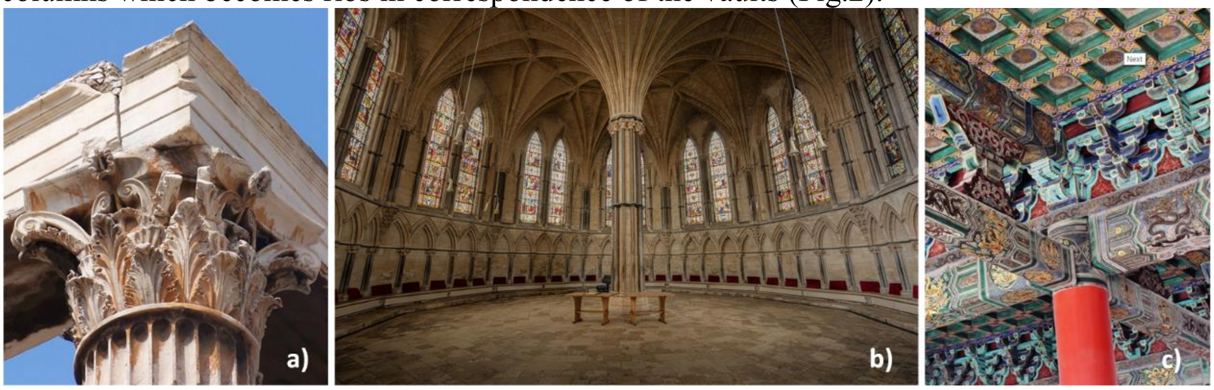

Fig.2. Columns and capitals inspired by nature in: a) Korinthian column capital, temple of Zeus Olympian, Athens; b) Lincoln Cathedral Chapter House, UK; c) Dougong, Forbidden City, Beijing, China.

The level of accuracy in the structural design and optimization evolved from the graphic static, extensively used by Antony Gaudi, to the most recent finite element methods through several approximated analytical methods. A key step in the structural optimization is the work carried out at the Institute for Lightweight Structures (ILEK) at the University of Stuttgart between 1964 and 1990 under the supervision of Frei Otto who investigated and tested new form-finding techniques inspired by nature.

One of the most relevant studies for this type of structures is the design for the Stuttgart Airport Terminal by Von Gerkan, Marg+Partner (1991). The project (Fig.3b) is based on innovative form-finding techniques (Fig.3a) which has been proven to be extremely effective in the optimization of the structure[5].

The success of tree-like structures continued in the last decades with several iconic projects, from the concrete structure designed by Pier luigi Nervi for the Palazzo del Lavoro in Turin (1961) to the Tree of Life for the Expo 2015 in Milan, from the Centre Pompidou in Metz by Shigeru Ban and Jean de Gastines to the Tote Banqueting Hall designed by Serie Architects in Mumbai. The combination of a tree-like rigid structure and a membrane cladding lead to a new generation of lightweight structures characterized by the efficient use of the materials and cost-effective manufacturing techniques. Like the examples shown in Fig. 4, given the rigid boundaries and the level of pretention of the membrane, the double curved surface can be easily obtained through form-finding techniques and manufactured with reasonably simple cutting pattern.

Fig.3. Stuttgart Airport Terminal: a) Frei Otto's hanging models of branching systems[4]; b) Internal view of the Stuttgart Airport Terminal.

Fig.4. Tree-Like Fractal Structures: a) Tensile umbrella in Delhi, India; b) Inverted cone for the shopping mall "Parc des Vergers de la Plaine", Chambourcy, France; c) Folding Umbrellas, SL-Rash; d) Centre for Nature Interpretation in Melilla, North Africa

2 THE DESIGN OF A SMALL SPAN TENSILE ROOF FOR THE PRIORY PARK INFANT SCHOOL IN ST NEOTS, UK

The structure has been designed to replace the loss of the school's horse chestnut tree providing shaded creative space for outdoor learning activities. The tree was the symbol of Priory Park Infant School in St Neots and the team of designers decided to create a tensile roof able to mimic the size and the shape of the original tree and, at the same time, to provide a modern and functional structure which could become the new emblem of the school and promote its image of forest school status.

The shape of the tree crown (Fig. 5a) has been obtained starting from the geometry of a truncated icosahedron (Fig. 5c), an Archimedean solid with 12 regular pentagonal faces, 20 regular hexagonal faces, 60 vertices and 90 edges (Fig. 5b).

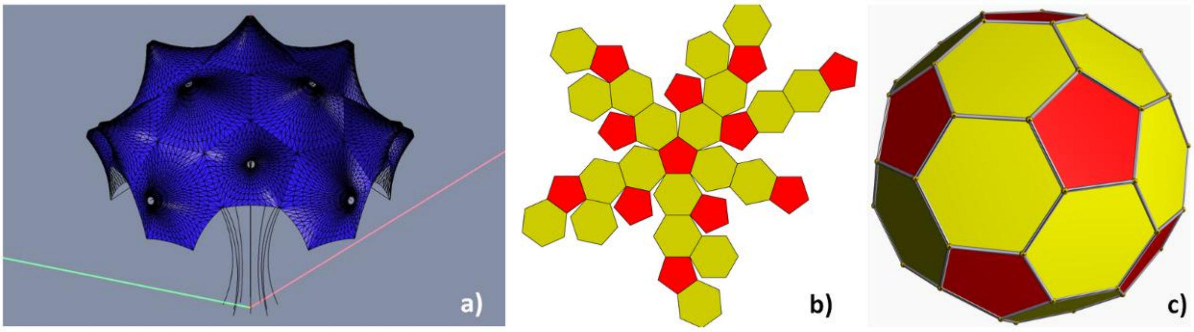

Fig.5. Geometrical model of the tensile roof: a) 3D model in Rhino; b) Net of a truncated icosahedron[6]; c) Colored faces of a truncated icosahedron[6];

2.1. Steel frame

The steel frame is made of a set of independent curved circular hollow sections which are fixed to the concrete foundation and grouped together to mimic the shape of the tree and to improve the overall stability of the structure. Each tube ends with a circular support for each module of the membrane and provide the anchoring point for the cables used for the tensioning of the surface. The details (Fig. 6) have been modeled in 3D with Rhino.

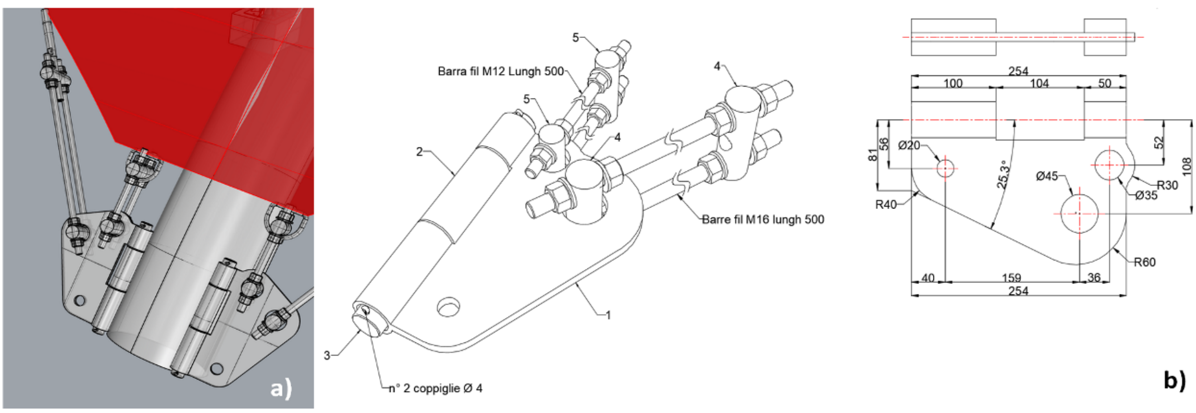

Fig.6. Digital model of the structural connections: a) 3D view; b) Blueprints generated from the digital model

2.2. Membrane

The membrane roof will be manufactured with a PVC coated Polyester fabric which is one of the most used textile membranes in the building industry due to the good compromise of price and performance[7].

The 3D geometry has been generated using the form-finding module of ixCube 4-10 which is based on the force density method. The overall target is to have a level of pre-stress between 1kN/m and 1.5kN/m with the only exception of the extremity of the cones. The stability of the membrane roof has been also investigated under the expected wind and snow loads.

The cutting pattern will follow the modular geometry of the faces of the truncated icosahedron. Each pentagon (or hexagon) will be subdivided in five (or six) triangles which will be subsequently welded together to obtain the final 3D geometry.

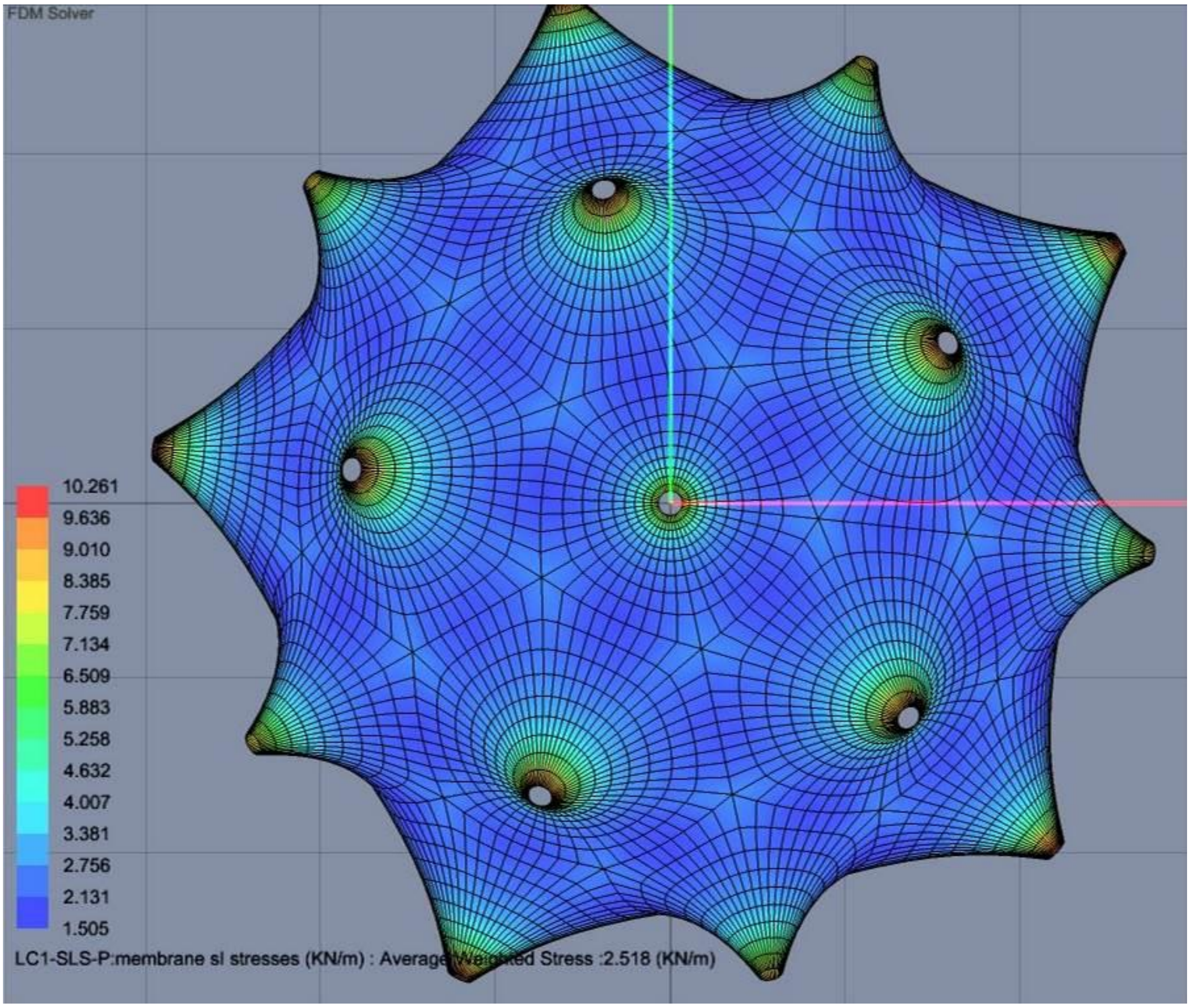

Fig.7. Digital model of the membrane structure with color mapping for a visual depiction of the expected stress distribution in the membrane after the initial installation and pre-stress.

2.3. Installation

The tensile roof is designed to be permanent structure. The design has been optimized in order to minimize the need of large lifting equipment. The components of the structure will be transported on site with a truck equipped with a hydraulic crane able to lift the steel components. The curved tubes will be bolted to a reinforced concrete platform and connected in order to improve the lateral stability. Once the steel frame is installed, the membrane will be lifted and connected in correspondence of the circular supports placed at the end of each tube. Finally, the membrane will be tensioned through the adjustment of the length of the cables in correspondence of the edges the vertex of the truncated icosahedron.

4 CONCLUSION

The paper describes the design of a tensile roof for an infant school designed to mimic and replace the original horse chestnut tree emblem of the school. The project is the result of a KTP research project funded by Innovate UK in order to develop new membranes structures based on advanced digital modelling and manufacturing techniques. The structure will be manufactured and installed by Insde2Outside Ltd which aims to open a new market for bespoke membrane structures.

5 ACKNOWLEDGMENTS

The project is designed by Insde2Outside Ltd in the UK, as part of an Innovate UK funded Knowledge Transfer partnership (KTP9912) with Nottingham University. The software used for the structural design of the tensioned membrane, ixCube 4-10, has been kindly provided by IxRay ltd and the Master of Membrane Structures at Anhalt University of Applied Sciences, Dessau, Germany.

REFERENCES

[1] http://ktp.innovateuk.org/

[2] I.M. Rian, M. Sassone, *Tree-inspired dendriforms and fractal-like branching structures in architecture: A brief historical overview*, Frontiers of Architectural Research (2014) **3**: 298–323

[3] J. Sánchez-Sánchez, F.E. Pallarés, M. T. Rodríguez-León, *Reciprocal Tree-Like Fractal Structures*, Nexus Netw J (2014) **16**:135–150.

[4] W. Nerdinger, *Frei Otto Complete Works: Lightweight Construction Natural Design*. (2005) Birkhäuser, Basel; Boston; Berlin.

[5] Flamur Ahmeti (2007), *Efficiency of Lightweight Structural Forms: The Case of Treelike Structures - A comparative Structural Analysis.* MSc Program "Building Science & Technology“, TU Vienna.

[6] https://en.wikipedia.org/wiki/Truncated_icosahedron.

[7] P. Beccarelli, *Biaxial tests and procedures for fabrics and foils*, Springer Briefs in Applied Sciences and Technology, (2015), Springer, New York.